Characterization of a digital camera as an absolute tristimulus colorimeter

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ABSTRACT

An algorithm is proposed for the spectral and colorimetric characterization of digital still cameras (DSC) which allows to use them as tele-colorimeters with CIE-XYZ color output, in cd/m^2. The spectral characterization consists of the calculation of the color-matching functions from the previously measured spectral sensitivities. The colorimetric characterization consists of transforming the RGB digital data into absolute tristimulus values CIE-XYZ (in cd/m^2) under variable and unknown spectroradiometric conditions. Thus, at the first stage, a gray balance has been applied over the RGB digital data to convert them into RGB relative colorimetric values. At a second stage, an algorithm of luminance adaptation vs. lens aperture has been inserted in the basic colorimetric profile. Capturing the ColorChecker chart under different light sources, the DSC color analysis accuracy indexes, both in a raw state and with the corrections from a linear model of color correction, have been evaluated using the Pointer'86 color reproduction index with the unrelated Hunt'91 color appearance model. The results indicate that our digital image capture device, in raw performance, lightens and desaturates the colors.
Keywords: device modeling and characterization, digital cameras, device limitations, color correction

1. INTRODUCTION

From image capture to the acceptable color reproduction in an output device display (softcopy) or printer (hardcopy), the generic imaging chain[1] or workflow for digital photography consists of several successive stages (Fig. 1), each of which is described in terms of the state of the image. At first, the image consists of the scene being photographed as seen through the zoom lens of the electronic still picture camera. Next, the image sensor (CCD or CMOS) and its associated electronics (internal gain, white balance, ADC) convert the optical image into a digital image representing the device-dependent raw response of the camera. Without taking into account the aspects of color quantization and conversion scaling, image compression and data format file, the image is transformed next to a device-independent representation (CIE-XYZ, CIE-L*a*b*), a representation that is referred to the scene itself, not to any input or output device. This color transformation (in cursive in Fig. 1) between the raw RGB and CIE-XYZ spaces is the aim of this work, as in the ISO 17321[1] standard.

At the center of the diagram, the image is color-rendered, i.e., the image may suffer some transformations in order to compensate for the differences in the input and output viewing conditions, tone and gamut mapping, etc, so these operations are typically proprietary and irreversible. In the color rendering stage, the state of the image changes from input-referred to standard output-referred (sRGB, ICC PCS, etc), but is still device-independent. Next, the image is transformed to a device-dependent representation reversing the device color characterization model so that the image can be downloaded in an output-ready state to a specific output device. A final viewable image is produced by this output device as either softcopy (displays: CRT, LCD, etc) or hardcopy (color printers: ink-jet, sublimation, offset, etc).

1.1. Selection of the raw DSC-RGB color space

When a digital image capture device (scanner or camera) is color characterized it is necessary to take into account both the details of characterization and calibration. The characterization model associated to a color device consists of a reversible analytical model linking the digital output levels RGB of the device and the absolute tristimulus values XYZ

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(in cd/m^2) of the CIE standard observer. Even if the spectroradiometric conditions in a scene are fixed, there is a great variety of factors in a digital image capture device that can alter the RGB encoding the same scene. The lens aperture or f-number N of the zoom-lens, the photosite integration time t of the electronic shutter and the type of color architecture (3-CCDs, stripe color filter, etc) of the image sensor can be called extrinsic factors because they act before the analogic and optoelectronic image formation. On the other hand, the internal gain, the electronic white balance and the digitalization parameters are intrinsic factors because they mediate between the analogic and the digital stages of image formation. In principle, any variation of the exposure level H over the image sensor due to the lens aperture N (illuminance scale exposure series) changes the raw DSC image data but not the raw DSC-RGB space associated to its spectral sensitivities. The same should happen with time scale exposure series. Therefore, a color characterization model of digital image capture devices should include at least the influence of the lens aperture N or the photosite integration time t. We shall present in this work a general color characterization model which includes the influence of the lens aperture or f-number N of the zoom-lens using a luminance adaptation algorithm.

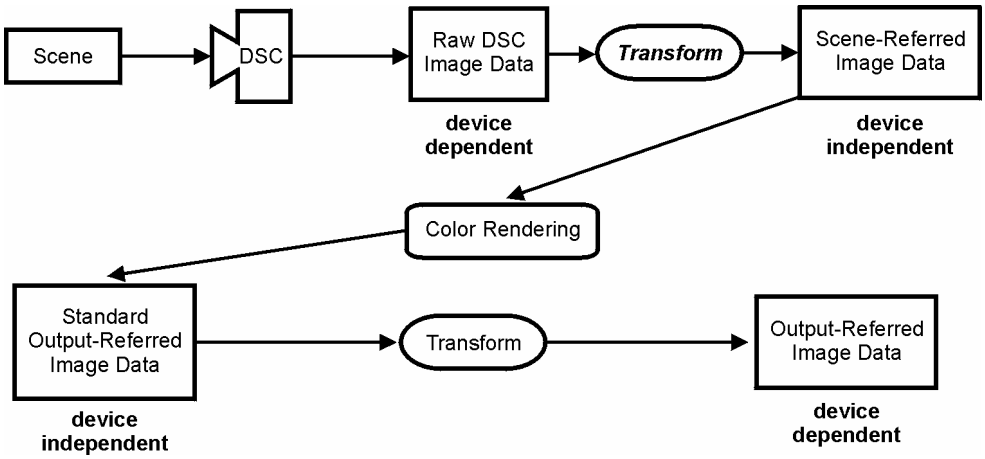

Figure 1: Imaging chain for digital photography.

1.2. Basic colorimetric profile for DSCs

Therefore, the color characterization of digital image capture devices consists of calculating the colorimetric profile between RGB device space and the CIE-1931 XYZ space associated to the same color stimulus under uncontrolled color and intensity illumination conditions. In this way, the digital image capture device should perform as an absolute tele-colorimeter because the color output data should be in cd/m^2, i.e., the color device should be simultaneously a colorimeter and a luminance meter (Fig. 2). Thus, from the raw DSC image data, i.e. digital output levels DOL_k (k = R, G, B color channels), we could obtain the absolute tristimulus values CIE-XYZ (in cd/m^2) as with a tele-spectroradiometer (TSRM in Fig. 2; Eq. 1). Using a vector space notation[2], these values are as follows:

$$\mathbf{t}_{\mathbf{XYZ}} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = K_m \mathbf{T}_{\mathbf{XYZ}}{}^{\mathrm{t}} \cdot \mathbf{c}\,, \tag{1}$$

where K_m is 683 lm/W, $\mathbf{T}_{\mathbf{XYZ}} = [\,\bar{\mathbf{x}}\ \bar{\mathbf{y}}\ \bar{\mathbf{z}}\,]_{41\mathrm{x}3}$ are the color-matching functions in matrix format from 380 to 780 nm at 10 nm steps and $\mathbf{c} = \mathrm{diag}(\mathbf{L})\cdot\boldsymbol{\rho}$ is the color stimulus, resulting of the spectral reflectance $\boldsymbol{\rho}$ of the object and the light source or illuminant $\mathbf{L}$ in W/sr·m^2. In what follows, $\mathbf{A}^{\mathrm{t}}$ denotes the transpose of the matrix $\mathbf{A}$, and, diag($\mathbf{x}$) the diagonal matrix from the vector $\mathbf{x}$.

If a digital still camera (DSC) could perform simultaneously like a colorimeter and a photometer, it would join to the performance of a tele-spectroradiometer-colorimeter (TSRM in Fig. 2) the advantages of being able of simultaneously measuring all the visual field. Such a color device would have numerous industrial and scientific applications: spatial and color characterization of the displays, micro-colorimetry, comparative of camera models according to the raw color reproduction, color appearance models, color management, etc.

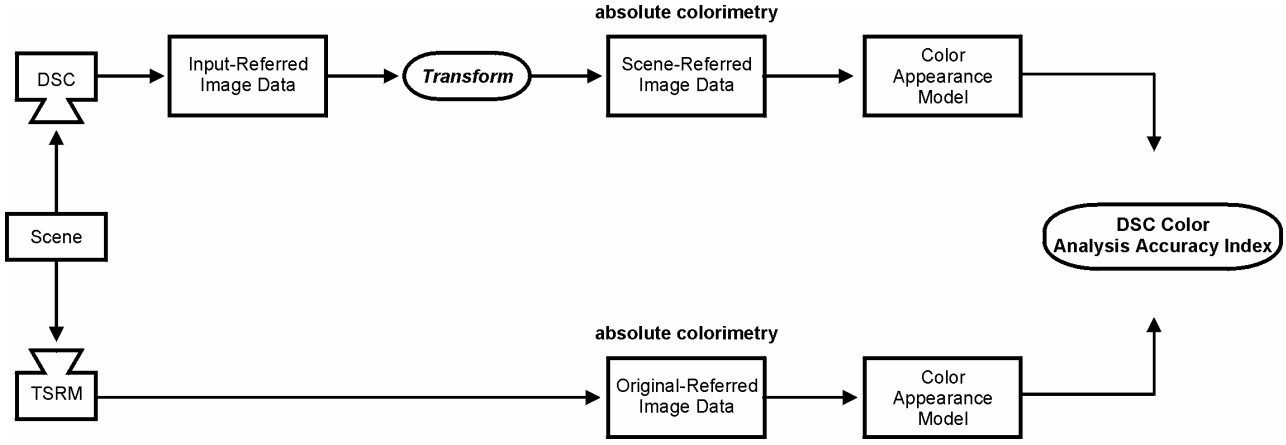

Figure 2: Colorimetric chain for obtaining the DSC color analysis accuracy index.

The basic colorimetric profile[2] is a 3x3 matrix **M** which should associate the RGB relative colorimetric values or $\mathbf{t'_{RGB}}$ with the relative tristimulus values $\mathbf{t'_{XYZ}}$ normalized to the equal-energy stimulus or *adapted white* $\mathbf{E} = [1, 1, ..., 1]^t$ (Eq. 2) and not to the *adopted white* according to the terminology used in ISO 17321[1]. In this way, the estimated relative tristimulus values XYZ (in prime) should be as follows:

$$\hat{\mathbf{t}}'_{\mathbf{XYZ}} = \mathbf{M} \cdot \mathbf{t}'_{\mathbf{RGB}} \quad \text{with} \quad \mathbf{T_{XYZ}}^{t} = \mathbf{M} \cdot \mathbf{T_{RGB}}^{t} . \tag{2}$$

If our purpose is to get an absolute estimation, in cd/m^2, of the tristimulus values XYZ, we must link a group of luminances associated to the equal-energy stimulus or illuminant **E** with the corresponding RGB data of the color device. This relationship is the *camera opto-electronic conversion function*[3] (OECF). For any scale exposure series – varying the f-number N of the zoom lens or the photosite integration time t– and object luminance L (in cd/m^2), the *OECFs* are described as follows:

$$\mathbf{t}'_{\mathbf{RGB}} = \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} OECF_R(L) \\ OECF_G(L) \\ OECF_B(L) \end{bmatrix} . \tag{3}$$

Taking into account L_E as the luminance of the adapted white[1,3] or the perfect white diffuser inside the scene, the relative colorimetric profile is obtained then reversing the camera *OECFs* as follows:

$$\hat{\mathbf{t}}'_{\mathbf{XYZ}} = \frac{1}{L_E} \mathbf{M} \begin{bmatrix} OECF_R^{-1}(R) \\ OECF_G^{-1}(G) \\ OECF_B^{-1}(B) \end{bmatrix} . \tag{4}$$

In principle, the choice of the reference white in the color transformation between the two color spaces is crucial. If we wish to use a digital still camera like a photocolorimeter, it is indispensable to select the equal-energy illuminant or adapted white **E** as reference white, and not the adopted white of the scene, which is associated to the electronic white balance according to the chromaticity of the light source or illuminant. However, the ISO 14524 standard[3] proposes an algorithm to obtain the photometric function *OECF* with fixed lens aperture N or photosite integration time t and any illumination different from illuminant **E**. This standard is used in turn in the ISO 17321-2 standard[1] to obtain the relative colorimetric profile associated to a digital still camera (DSC).

From the available options[4,5] to obtain the basic colorimetric profile **M**, we shall use the *Maximum Ignorance by Least Squares regression* option (MaxIgLS), i.e., only the spectral sensitivities of the color device are known. If $\mathbf{T_{XYZ}}$ and $\mathbf{T_{RGB}}$ are the color-matching functions of the CIE observer and the color device, the basic colorimectric profile **M** is:

$$\mathbf{M} = \mathbf{T_{XYZ}}^{t} \cdot \mathbf{T_{RGB}} \cdot \left(\mathbf{T_{RGB}}^{t} \cdot \mathbf{T_{RGB}}\right)^{-1}. \tag{5}$$

In the other options or algorithms (*No-Maximum* and *Minimum Ignorance*) it is customary to use the same samples both for training and test under well fixed spectroradiometric conditions, so the total color difference ΔE metrics is excellent. In this work we shall present a color characterization model which performs well independently of the previous knowledge of the intensity and the chromaticity of the light source and the spectral content of the objects inside the scene. The training set is the empirical determination of the color-matching functions[6] $\mathbf{T_{RGB}}$ of the color device, and, the test set is the ColorChecker chart under three real light sources (not CIE illuminants) inside a non-standard viewing booth. The spectral characteristics of the light sources and the patches of the color chart are not used.

1.3. DSC Color Analysis Accuracy Index

As the ISO 17321-2[1] standard, we are interested the methods for deriving transformations from digital camera data in order to estimate scene colorimetry (Fig. 2), including an error minimization method (color correction) and a metric for quantifying the errors in scene colorimetry estimation. A first approximation is to use only the spectral sensitivities of the color device quantifying the common volume between the sub-vectorial spaces associated to the two sets of color-matching functions $\mathbf{T_{RGB}}$ and $\mathbf{T_{XYZ}}$. This approach was proposed by Neugebauer as the quality factor q in 1956 and it has been enlarged with new *quality factors*[7] or figures of color merit for image capture devices, both minimizing the mean-squared error metric in CIE-XYZ or CIE-L*a*b* spaces. However, these algorithms do not take into account a direct comparison between the original-referred and the scene-referred image data. To do this, it is necessary to translate the problem into a color appearance model format. Only if we use from the beginning the absolute colorimetric format, can we work with realistic color appearance models. If we prefer to use the relative colorimetry format the simplest color appearance model available is CIE-L*a*b* space. This duality between the two kinds of colorimetric format, absolute (in cd/m^2) and relative, involves also the duality between unrelated and related colors and the way that the camera or scanner captures a scene. Basically, without taking into account flare effects, these digital image capture devices encode the incident light in isolated format. Therefore, although human color perception should be described with complicated color appearance models for related colors, which is the conventional configuration of the colors inside a image, the unrelated character of the image capture of the cameras and scanners should suggest to us at first the application of any single stimulus appearance model, i.e. with black surround, and not an image appearance model following the ISO terminology[1]. In this work, unlike the ISO 17321-2 standard, we are going to implement the unrelated Hunt'91 color appearance model[8] to compute an alternative *DSC color analysis accuracy index*.

The digital image capture devices (scanners and cameras) are pseudo-colorimeters because their spectral sensitivities, due to engineering and technological conditions[9], are not exact linear combinations of the CIE-XYZ color matching functions (Luther condition), so systematic color reproduction errors will unavoidably appear. In spite of this, decades of experience in color photography and television have shown that acceptable color reproduction for typical scenes can be achieved using non-colorimetric RGB sensitivity curves. Unfortunately, performing some of the current color correction techniques it is very difficult to know the true quality level or accuracy index of the color reproduction of these color devices, i.e., whether in raw state the red gamut is encoded more yellowish or the blue gamut is encoded more darker. In principle, because these color deviations are associated to some systematic error sources, they could be automatically compensated. Nevertheless, we think that it is very interesting also to study the DSC color analysis accuracy index in raw state in order to compare different digital image capture devices.

This approach requires to break down the raw color deviations of the device into the contributions of the perceptual chromatic variables -brightness, hue and colorfulness for unrelated colors. Moreover, we must take into account also the relative (including the sign) and absolute partial color differences and they can be divided into the principal hue segments -red, yellow, green and blue. This algorithm of color reproduction quality has been proposed already by M.R. Pointer in the form of a *color reproduction index*[9,10] *CRI*. If *QcI* is the combined index of the brightness differences ΔQ, *HcI* is the combined index of the hue differences ΔH and *McI* is the combined index of the colorfulness differences ΔM for a standard color chart the color reproduction index *CRI* is computed as follows:

$$CRI = \frac{QcI + k \cdot HcI + McI}{k+2}. \tag{6}$$

where k is a weight factor, usually equal to 2, reflecting that perceptual tolerances are smaller for hue than for brightness and colorfulness differences. If all the absolute and relative color differences were null, by means of a simple normalization, the combined indexes *QcI*, *HcI* and *McI* and the overall index *CRI* should be all equal to 100, so this upper bound indicates the perfect color reproduction or scene colorimetry estimation.

In short, a general color characterization of any digital still camera will be presented in this work in order to convert this color device into an absolute tele-colorimeter. The proposed algorithm is divided in two parts: spectral and colorimetric characterizations. The spectral characterization algorithm[6] has already been published but part of the results will be necessary to solve the colorimetric characterization algorithm. Let $\mathbf{t_{XYZ}}$ be the original-referred image data (Eq. 1; Fig. 2), just as they are obtained by a tele-spectrocolorimeter, and $\hat{\mathbf{t}}_{\mathbf{XYZ}}$ the scene-referred image data from the proposed colorimetric profile (Eq. 4) with luminance adaptation. We are going to test this reproduction model capturing the ColorChecker chart under three light sources varying selectively the f-number N of the zoom lens of the camera, making no assumptions about the scene spectral radiance correlation statistics (maximum ignorance case). We shall show that the original-referred image data of the unclipped colors can be estimated by regression using a linear model of color correction, composed by a tristimulus vector $\mathbf{A_C}$ and the scaling diagonal matrix $\mathbf{B_C}$. Redefining finally the raw colorimetric profile as $\mathbf{B_C} \cdot \hat{\mathbf{t}}_{\mathbf{XYZ}}$, the DSC color accuracy analysis indexes for the raw (without $\mathbf{A_C}$) and compensated colorimetric profiles (with $\mathbf{A_C}$) will be calculated using the color reproduction index (*CRI*) with a color appearance model for unrelated colors (Hunt'91).

2. METHODOLOGY

The experimental set-ups are basically one for the spectral characterization (monochromator set-up[6]) and another for the colorimetric characterization (viewing booth set-up). Our digital image capture device consisted of a Sony DXC-930P 3CCD-RGB camera with a zoom lens (model VCL-712BXEA) connected to a Matrox MVP-AT 850 frame grabber, inserted into a PC unit. Among the fixed initial conditions, which might alter the color output, we set the electronic white balance to 5600 K in manual menu-mode (offset value) and configured the analog-digital converter to work with the raw response space. In all exposure processes, the photosite integration time t of the electronic shutter was fixed to offset value t_0 = 20 ms so the exposure determination was realized varying carefully the f-number N of the zoom-lens.

Along all the experiments, with centered capture of visible light, we shall consider the spectral exposure $H(\lambda)$ to be proportional to the spectral radiance $L_e(\lambda)$ of the object and the photosite integration time t and inversely proportional to the f-number N:

$$H(\lambda) \propto \frac{L_e(\lambda)}{N^2} t \,. \tag{7}$$

Using monochromatic light, we shall suppose besides that the reciprocity law –identical values of spectral exposure yield identical responses even if the lens aperture N or the exposure time t change– is verified[11] in digital photography.

About the physics of image capture, we shall suppose that the univariance principle holds (Eq. 8). If $n_{pe}(\lambda)$ is the number of spectral generated photoelectrons from the incident photon rate $n_\nu(\lambda)$, the total number will be n_{pe} according to the univariance principle. Interchanging in the final optoelectronic step the spectral generated photoelectrons $n_{pe}(\lambda)$ by spectral digital output levels $DOL(\lambda)$, the total output digital level DOL is:

$$n_{pe} = \sum_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} n_{pe}(\lambda)\Delta\lambda = \sum_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} n_\nu(\lambda) QE(\lambda)\Delta\lambda \quad \Rightarrow \quad DOL = \left(2^{bits}-1\right)\sum_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} NDOL(\lambda)\Delta\lambda = \left(2^{bits}-1\right)\sum_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} H(\lambda) r(\lambda, H)\Delta\lambda \,. \tag{8}$$

where $QE(\lambda)$ is the spectral quantum efficiency, or quantum version of the spectral responsitivity $r(\lambda, H)$ of the digital image capture device, and $NDOL$ is the normalized digital output level.

The first step to characterize a digital image capture device as an absolute tristimulus colorimeter is the spectral characterization. This has been done in our previous work[6]. We have shown that the univariance principle may be

rewritten using the analytical expression of the *opto-electronic conversion spectral functions* (*OECSFs*) measured from the monochromator experiment as follows:

$$DOL_k = \left(2^{bits} - 1\right) \sum_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} \left[a_{\lambda k} + \frac{b_{\lambda k}}{1 + \exp\left(-\dfrac{H_\lambda - c_{\lambda k}}{d_{\lambda k}} \right)} \right] \Delta\lambda \quad , \tag{9}$$

where H_λ is the dense version of the spectral exposure (Eq. 7) and the values $\{a, b, c, d\}$ are the fitting parameters for each wavelength and color channel (k = R, G, B) of the sigmoid function that models the empirical relationship between the normalized output digital levels $NDOL_k$ and the spectral exposure $H(\lambda)$.

The second step is the colorimetric characterization. The necessary experimental procedure consists of capturing the GretagMacbeth ColorChecker chart under different light sources. The used lamps were a halogen lamp (INC), a metal halide lamp (HWL) and a daylight fluorescent lamp (DAY). To reduce flare, the walls and the base of the viewing booth were black painted and all the patches of the chart except one were masked. As was commented in the introduction, this capture condition justifies also the use of a color appearance model for unrelated colors (Hunt'91) to obtain the DSC color analysis accuracy index. A Photo Research PR-650 tele-spectroradiometer, in the same position as the camera, was used to measure the spectral radiances $L_e(\lambda)$ of all the chart patches under these light sources (Fig. 3).

The camera and frame grabber conditions were the same as in the above experiment[6], that is, the electronic white balance was fixed by control menu at 5600 K, except the f-number N of the zoom lens which was varied to maximize dynamic range of raw digital data (N = 4 for INC capture, N = 5.6 for HWL and DAY captures). In spite of this, some colors were not encoded optimally because at least one of the three associated output digital levels was clipped, due to underexposure or saturation. From the possible 72 colors with the three captures, 53 useful colors remained. On the other hand, due to vertical illumination non-uniformity inside the viewing booth and according to the relative colorimetric profile (Eq. 4), the luminances L_E of a Halon reference white, used as adapted white, were measured by the tele-spectroradiometer in the 72 positions of the color chart under the three light sources.

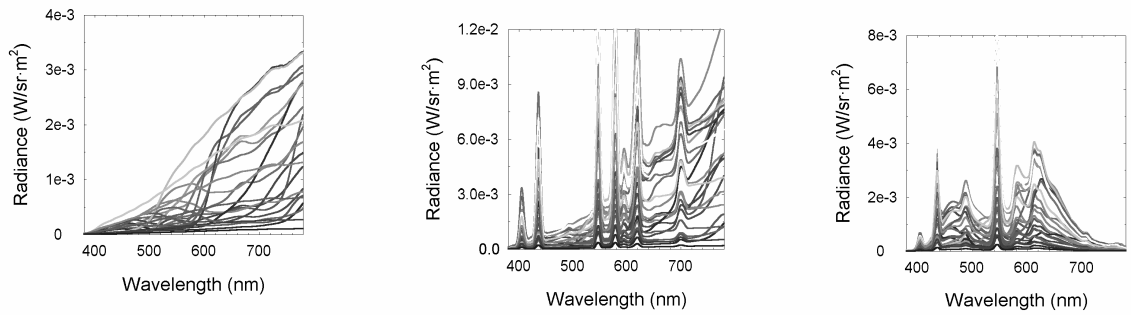

Figure 3: Color stimuli of the ColorChecker chart inside the viewing booth under incandescent (left), metal halide (center) and daylight fluorescent (right) lamps.

From our previous work the color matching functions $\mathbf{T_{RGB}}$ (Fig. 4, left) were obtained for our color device. According to Eq. 5, the basic colorimetric profile $\mathbf{M}$ is:

$$\mathbf{M} = \mathbf{T_{XYZ}}^{\mathrm{t}} \cdot \mathbf{T_{RGB}} \cdot \left(\mathbf{T_{RGB}}^{\mathrm{t}} \cdot \mathbf{T_{RGB}}\right)^{-1} = \begin{bmatrix} 1.5798 & 0.4016 & 0.3643 \\ 1.0086 & 1.6157 & 0.0742 \\ -0.0107 & 0.1573 & 2.0189 \end{bmatrix}. \tag{10}$$

Now we may evaluate graphically the fitting by comparing the estimated color matching functions $\mathbf{T_{RGB}}\cdot\mathbf{M}^t$ with the true ones $\mathbf{T_{XYZ}}$ (Fig. 4, right). Looking at this graph it is clear that the spectral functions $\mathbf{T_{RGB}}$ are not strictly color matching functions, so it seems correct to denote them as color matching pseudo-functions.

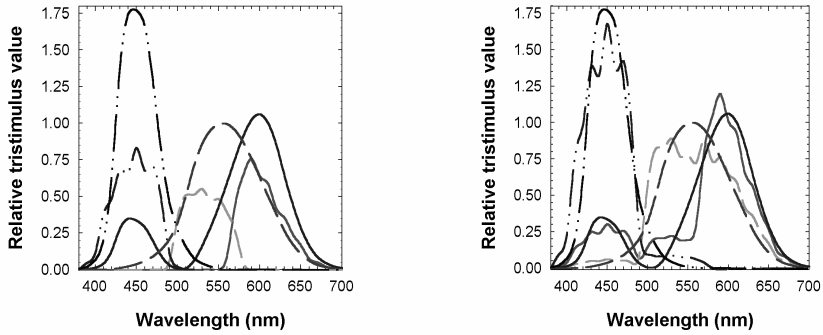

Figure 4: Left: Color-matching pseudo-functions of the Sony DXC-930P video camera (broken lines) compared to the standard observer CIE-1931 XYZ (smooth lines). Right: Estimated CIE-1931 XYZ color-matching functions applying the basic colorimetric profile MaxIgLS of our color device. (Solid line: R or X channel; dashed line: G or Y channel; dash-dot-dot line: B or Z channel)

Additional information necessary to solve the colorimetric characterization and included in our previous work is the colorimetric or *equal-energy white balance test*. These are key data because they inform us about the ratio among the areas beneath the color matching functions associated to our color device. In the CIE-1931 XYZ space, this ratio is 1:1:1 but, although the electronic white balance was fixed to 5600 K by control menu, the obtained ratio was bal_R = 0.8642, bal_G = 0.6839 and bal_B = 1. One consequence of taking bal_B = 1 is that the color matching functions $\mathbf{T_{RGB}}$ are scaled relative to the blue channel and not relative to the absolute scaling of the color matching functions $\mathbf{T_{XYZ}}$. This inconvenient can be solved using color correction techniques such as we shall apply further in this section.

In the other hand, we present a reproduction model with luminance adaptation in order to estimate the absolute tristimulus values $\mathbf{t_{XYZ}}$ (in cd/m^2), such as they might be obtained by a tele-spectrocolorimeter. Complementarily, a new DSC color analysis accuracy index will be proposed implementing the Hunt'91 unrelated color appearance model[8] into the Pointer'86 color reproduction index *CRI*[9,10].

2.1. Ideal Gray Balance

A gray balance algorithm is used in the first place in order to obtain the relative colorimetric RGB values from the digital RGB output levels. If $NDOL_k$ is the normalized digital output level for each color-channel, the relative RGB values are obtained from the ratio among the areas beneath the color-matching functions associated to the camera. Because this ratio is not 1:1:1, then the gray balance is applied as follows:

$$\begin{aligned} NDOL_k &= \frac{DOL_k}{2^{bits}-1} \quad , \quad k = R, G, B \\ R = \frac{NDOL_R}{bal_R} \quad &; \quad G = \frac{NDOL_G}{bal_G} \quad ; \quad B = \frac{NDOL_B}{bal_B} \end{aligned} \quad . \tag{11}$$

In this way, a RGB triplet equal to $[0.2, 0.2, 0.2]^t$ will be associated directly with a spectrally neutral color or any equivalent metamer for the device, even when, originally, their digital RGB encodings are very different.

2.2. Reproduction model with luminance adaptation

At the second stage, a colorimetric profile with luminance adaptation as a function of the control of the f-number N is proposed[12]. This algorithm adapts the relative and shorter dynamic range of the capture device response, limited by the spectral dynamic range of the *OECSFs*, to the real dynamic luminance range of any scene. For instance, let us consider

a gray scale test pattern (Fig. 5, center) well characterized by its XYZ tristimulus values (in cd/m^2) using a tele-spectroradiometer. This pattern is captured with certain values (N_0, t_0 = 20 ms) but the darker and lighter grays are clipped, respectively by dark noise and by saturation of the image sensor. If the lens aperture N decreases to N_1, the exposure level will raise, so the RGB digital output levels will be now different (Fig. 5, left) but the absolute tristimulus values XYZ (in cd/m^2) obtained by a tele-spectroradiometer will remain fixed. Now, the lighter grays will be again clipped at the expense of encoding optimally the darker grays, which were not clipped by dark noise. If the lens aperture N increases to N_2, the exposure level will decrease again, so the RGB digital output levels will be also different (Fig. 5, right) but the absolute tristimulus values XYZ will remain fixed. In turn, the darker grays will be again clipped at the expense of encoding optimally the lighter grays, which were not clipped by saturation. Then, the key question is how we can compensate the variation of the lens aperture N to obtain always the same CIE-XYZ values.

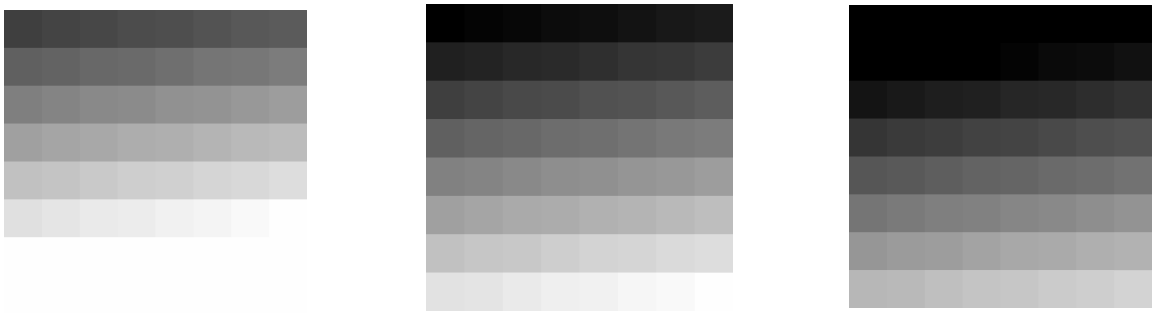

Figure 5: Significance of luminance adaptation balance. The gray scale test pattern was captured with lens aperture N_0 (center), with a lens aperture $N_1 < N_0$ (left) and with a lens aperture $N_2 > N_0$ (right).

Because our purpose in this work is to get an absolute estimation, in cd/m^2, of the tristimulus values XYZ, we must link the group of luminances of the former gray scale test pattern with the corresponding RGB data of our color device. This relationship was already introduced in the camera opto-electronic conversion function (OECF). If L is the luminance of the gray patch and L_E is the luminance of the perfect white diffuser inside the gray scale test pattern, for any exposure determination –varying the lens aperture N or the photosite integration time t–, the *OECFs* are described by Eq. 3, but they must reversed in order to insert correctly in the colorimetric profile (Eq. 4).

Unlike ISO 14524 standard[3], which proposes an empirical method to obtain the *OECFs* using a gray scale test pattern but not necessarily with the equal-energy illuminant **E**, we propose alternatively an algorithm to obtain the *OECFs* from the *OECSFs* using a simulated spectrally neutral gray scale test pattern illuminated by the equal-energy **E**. This procedure is equivalent to obtaining the responses of our color device to a large set of equal-energy stimuli **E** with variable uniform exposure levels H_E (with uniform radiance L_e and total luminance L_E). The total luminance L_E of each spectrally neutral gray patch is easily computed from its corresponding uniform radiance L_e. By fixating the photosite integration time $t = t_0$ = 20 ms (offset value) and giving free the lens aperture N, we can estimate the relative colorimetric RGB values for each gray patch or, equivalently, for each possible luminance L_E of the adapted white:

$$\frac{NDOL_k}{bal_k} = \frac{1}{bal_k}\sum_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} \frac{L_e}{N^2} t_0\, r_k\left(\lambda, \frac{L_e}{N^2} t_0\right)\Delta\lambda \;\Rightarrow\; \frac{NDOL_k}{bal_k} = \frac{1}{bal_k}\sum_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} \left[a_{\lambda k} + \frac{b_{\lambda k}}{1+\exp\left(-\dfrac{\frac{L_e}{N^2}t_0 - c_{\lambda k}}{d_{\lambda k}}\right)} \right]\Delta\lambda \qquad (12)$$

$$\text{with} \quad L_e = \frac{L_E}{K_m\left(\bar{\mathbf{y}}^{\mathrm{t}} \cdot \mathbf{E}\right)\Delta\lambda} = \frac{L_E}{683 \cdot 21.3714 \cdot 5}.$$

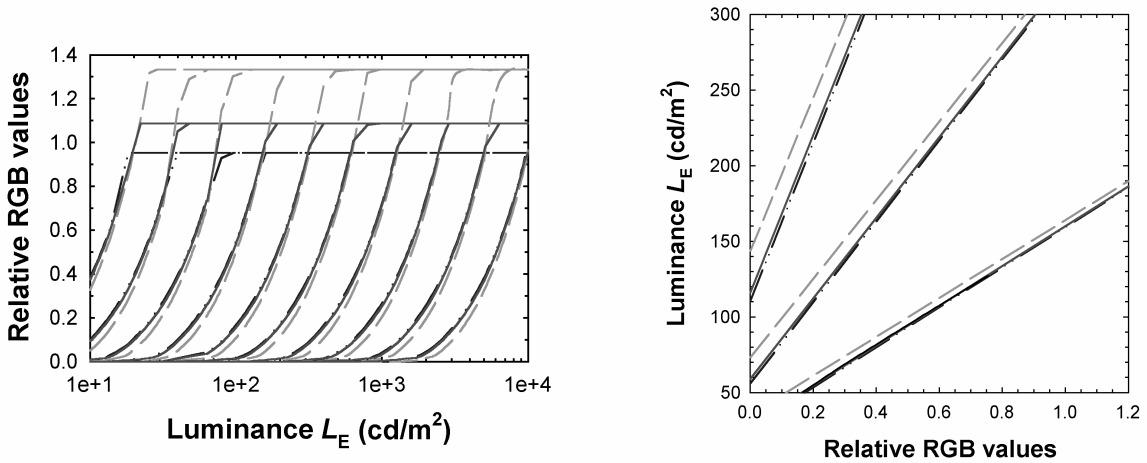

Figure 6: Balance of luminance adaptation of our digital image capture device. Left: each triad of OECFs curves belongs to a (*N*, fixed *t*) scale exposure series; from left to right, *N* = {1, 1.4, 2, 2.8, 4, 5.6, 8, 11.2, 16, 22.4}. Right: Enlarged representation of the inverse OECFs for the values *N* = 5.6, 4 and 2.8. Solid line: red channel; dashed line: green channel; das.dot-dot: blue channel.

Figure 6 (left) shows the balance of luminance adaptation of our digital image capture device, where each triad of *OECFs* curves belongs to a (*N*, fixed *t*) scale exposure series, where, from left to right, *N* = {1, 1.4, 2, 2.8, 4, 5.6, 8, 11, 16, 22.4}. It can be seen clearly that the *OECFs* curves are parallel. This is characteristic of any adaptation process, such as, for instance, the luminance adaptation described by any color appearance model[8,9]. For instance, a luminance of 100 cd/m^2 is encoded better with *N* = 2.8 than *N* = 4. On the other hand, a luminance of 1000 cd/m^2 is encoded optimally with both *N* = 8 (larger relative RGB values) and *N* = 11 (smaller relative RGB values), but if the rest of luminances of the scene is higher than this value, *N* = 11 is better than *N* = 8. If the rest of the luminances are lower, the opposite is true. Although the ISO DSC dynamic range of our color device is short (10:1 for the three color channels), we have found an algorithm to compensate this typical handicap in the majority of the digital image capture devices.

The obtained *OECFs* show a linear behavior in the mid-range when the x-axis (luminance) is not logarithmic, so the inverse *OECFs* can be considered as straight lines in this range except for the two tails associated to under-exposure and saturation. If the central zone of the last graph is enlarged (Fig. 6, right), two additional examples may be provided to help to understand the balance of luminance adaptation that it will be inserted in the reproduction model of our color device. A spectrally neutral gray with luminance 150 cd/m^2, gives nearly saturated responses in the three color channels with *N* = 2.8. On the other hand, with *N* = 4, it would be captured better. However, with *N* = 5.6 the signal is closer to the encoding noise level. Alternatively, with f-numbers *N* = 5.6, 4 and 2.8, we obtain the same relative colorimetric RGB encoding (0.3) for three grays of luminance 300, 140 and 70 cd/m^2. The key question is how we can compensate the variation of the lens aperture *N* to obtain the corresponding CIE-XYZ values.

Thus, the linear inverse *OECFs* can be modelled with a slope *m* and an offset value *h* for each color channel. Fitting the *m* vs. *N* and *h* vs. *N* data[12] we have found that these relationships are second-polynomial (Eq. 13; Table 1).

$$\begin{aligned} OECF_R^{-1}(R) &= m_R(N)\cdot R + h_R(N) \\ OECF_G^{-1}(G) &= m_G(N)\cdot G + h_G(N) \quad , \quad \text{with} \quad \begin{cases} m_k(N) = m_{0k} + m_{1k}N + m_{2k}N^2 \\ h_k(N) = h_{0k} + h_{1k}N + h_{2k}N^2 \end{cases} . \\ OECF_B^{-1}(B) &= m_B(N)\cdot B + h_B(N) \end{aligned} \tag{13}$$

Table 1: Fitting parameters of the second order polynomial of the slope and offset value of the inverse OECF for each color channel as a function of the lens aperture *N*.

CHANNEL	Slope "m"			Offset value "h"		
	m_0	m_1	m_2	h_0	h_1	h_2
R	2.9328	-1.1753	16.6933	-1.8589	0.7488	3.6676
G	4.2475	-1.7476	16.3244	-2.5022	1.0540	4.5253
B	2.1729	-0.7980	16.7543	-1.3288	0.4843	3.5035

Thus, without taking into account the luminance L_E of the adapted white and using directly absolute tristimulus values, we can describe now the colorimetric profile with luminance adaptation for any digital still camera as follows:

$$\textit{Original-referred image data (from a TSRM)}: \quad \mathbf{t}_{\mathbf{XYZ}} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \frac{\text{cd}}{\text{m}^2} \qquad \textit{Scene-referred image data (from a DSC)}: \quad \hat{\mathbf{t}}_{\mathbf{XYZ}} = \begin{bmatrix} \hat{X} \\ \hat{Y} \\ \hat{Z} \end{bmatrix} = \mathbf{M} \left\{ \begin{bmatrix} m_R(N) & 0 & 0 \\ 0 & m_G(N) & 0 \\ 0 & 0 & m_B(N) \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} h_R(N) \\ h_G(N) \\ h_B(N) \end{bmatrix} \right\} \frac{\text{cd}}{\text{m}^2} \tag{14}$$

3. RESULTS AND DISCUSSION

As it was advanced above, we use the viewing booth experiment with the ColorChecker chart under three light sources to test the former reproduction model with luminance adaptation ($N = 4$ for INC lamp, $N = 5.6$ for HWL and DAY lamps). Thus, the next step of the colorimetric characterization is to compare the estimated absolute tristimulus values XYZ from the model associated to the Sony DXC-930P CCD-RGB camera with the measured tristimulus values XYZ from a tele-spectroradiometer Photo Research PR-650.

3.1 Linear model of color correction

This comparison, plotted in Figure 7 for MaxLS basic colorimetric profile **M**, indicates that a linear model of color correction (Eq. 15) is necessary to predict better the scene colorimetry. This is understandable since our color device will show systematic reproduction errors because its color matching functions $\mathbf{T}_{\mathbf{RGB}}$ do not verify the Luther condition. Therefore, considering $\mathbf{A}_{\mathbf{C}}$ as the offset tristimulus vector and $\mathbf{B}_{\mathbf{C}}$ as the scaling diagonal matrix, the final reproduction model is:

$$\mathbf{t}_{\mathbf{XYZ}} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{A}_{\mathbf{C}} + \mathbf{B}_{\mathbf{C}} \cdot \hat{\mathbf{t}}_{\mathbf{XYZ}} = \begin{bmatrix} -32.65 \\ -35.02 \\ -30.10 \end{bmatrix} + \begin{bmatrix} 0.1851 & 0 & 0 \\ 0 & 0.1577 & 0 \\ 0 & 0 & 0.1937 \end{bmatrix} \cdot \begin{bmatrix} \hat{X} \\ \hat{Y} \\ \hat{Z} \end{bmatrix}. \tag{15}$$

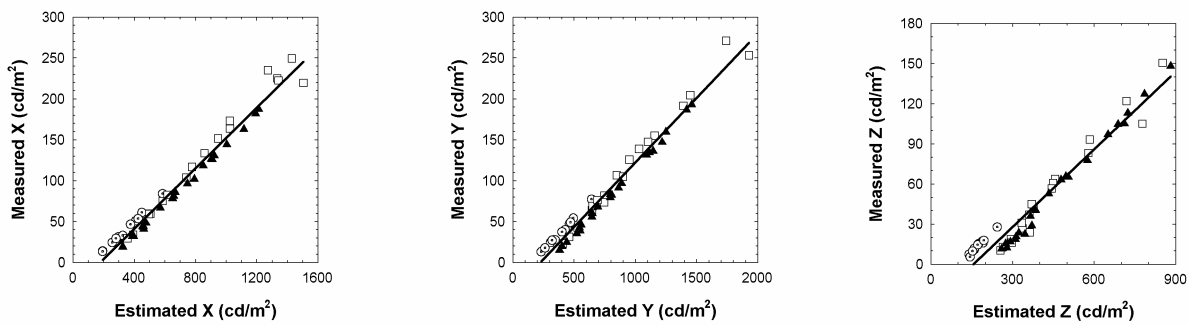

Figure 7: Linear correction (solid line) of the tristimulus value X (left), Y (center) and Z (right) of the color data using the raw reproduction model with luminance adaptation and basic colorimetric profile MaxIgLS. (Symbols: dotted circles, samples under incandescent lamp; squares: samples under metal halide lamp; triangles, samples under daylight fluorescent lamp.)

3.2 DSC Color Accuracy Analysis Index

In the final reproduction model with luminance adaptation there are two well differentiated colorimetric profiles, raw (without $\mathbf{A_C}$) and compensated (with $\mathbf{A_C}$), with which any DSC scene analysis error metrics can be calculated. As it was seen in the introduction, the color reproduction index *CRI* (Eq. 6) can be used to characterize statistically the absolute and relative color deviations of the chromatic perceptual variables of a color system in the principal hue segments (red, yellow, green and blue). This algorithm uses in turn a color appearance model for unrelated colors.

With this formalism, associating the *CRI* value to DSC scene analysis accuracy index, we can determine the raw color reproduction level of our color device and the effect of the correction tristimulus vector $\mathbf{A_C}$ on the *CRI* data of the raw colorimetric profile (Fig. 8 and 9). The analysis of the raw color reproduction level of our color device yields similar results as those we obtained with pseudo-uniform color space CIE-L*a*b*: the colors are systematically encoded lighter and more desaturated. It can be seen also the beneficial effect of the color correction model in these last figures, particularly in the relative deviations of brightness and colorfulness (Fig. 9, left and center). Regarding the estimation of hue (Fig. 9, right), the green, blue and red colors are relatively reproduced badly in raw state, but this systematic error is partially compensated in the red and blue colors at expense of the yellow and green colors.

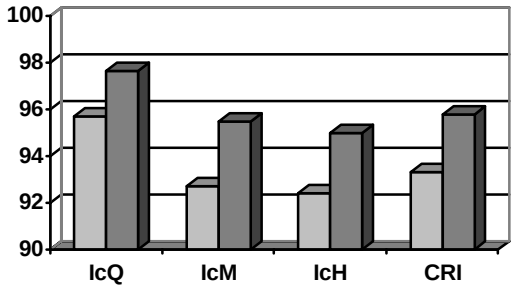

Fig. 8: Combined indexes of brightness *IcQ*, colorfulness *IcM* and hue *IcH* and total color reproduction index *CRI* of our color device with raw (light gray) and compensated (dark gray) colorimetric profile. The value 100 indicates perfect color reproduction.

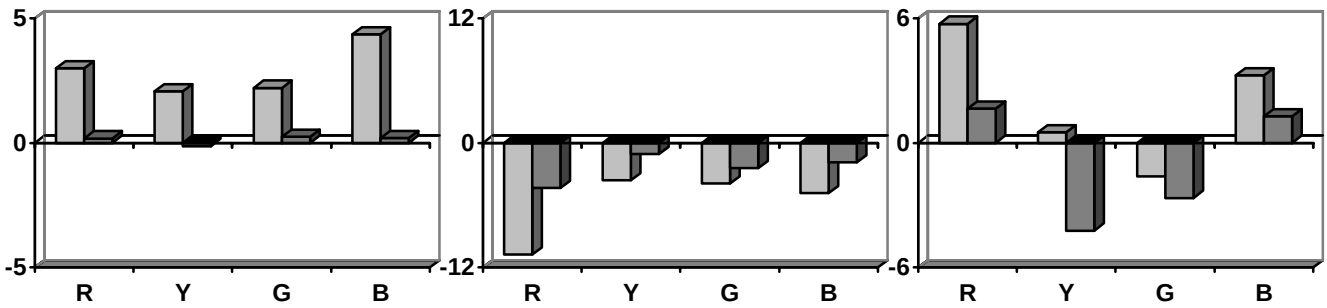

Fig. 9: Relative judgements of brightness (left), colorfulness (center) and hue (right) in each hue segment (Red, Yellow, Green, Blue) of our color device with raw (light gray) and compensated (dark gray) colorimetric profile.

4. CONCLUSIONS

A new color characterization model with luminance adaptation for digital still cameras has been proposed. This reproduction model, separated into two spectral and colorimetric characterization parts, would permit to use any digital camera a photometer and colorimeter, that is, we have designed a new instrument for measuring color. This means that, as in photometers and colorimeters, it is not necessary to know previously the spectral content of a scene for this new color instrument to perform correctly. To do this, it is necessary to separate the performance of the color device into raw and compensated. Due to the engineering and technological conditions of the design of the spectral sensitivities of these color devices, the raw color reproduction suffers some systematic color deviations very hard to detect. On the other

hand, following the guidelines of ISO 17321[1], we have also proposed a new DSC color analysis accuracy index implementing the Hunt'91 unrelated color appearance model[8,9] into the Pointer'86 color reproduction index[9,10]. However, in the formalism of this new reproduction model and DSC color analysis accuracy index, we have found that, in the case of our color device, the colors of any scene will be encoded lighter and more desatured in the raw state. Obviously, in these conditions, our color device cannot perform like a tele-colorimeter. However, with only a tristimulus vector ($\mathbf{A_C}$) as a color correction model, the scene colorimetry estimation improves significantly.

The proposed color characterization algorithm can be used as an analysis tool to compare different commercial cameras, particularly at the raw state. But, the major applications of a colorimetrically characterized digital camera as an absolute tele-colorimeter belong in the industrial colorimetry. If, to the former properties, it is added the ability of simultaneously measuring all the visual field, unlike the actual tele-spectroradiometers, this new color instrument is suitable for color characterization of displays, microscopic and/or non-homogeneous samples. But it is also an alternative solution to understand and control the color appearance of complex images, which is so important in the realistic color management flowcharts in digital TV and Cinema (camera and display interconnection).

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